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PRACTICE-ORIENTED PAPER

Green synthesis of nano-silica from olivine rock and its impact on the mechanical performance of geopolymer concrete composites

Hemn Unis Ahmed[1,2] · Rabar H. Faraj[3] · Aso Q. Hassan[4] · Yousif Osman Mohammad[5] · Khalid M. Omer[4] · Ahmed S. Mohammed[1] · Azad A. Mohammed[1]

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Abstract

Incorporating nanomaterials into geopolymer composites enhances their performance by improving microstructural properties through the formation of additional C–S–H, N–A–S–H, and C–A–S–H gels and effectively filling nanopores within the matrix. This study focuses on an innovative approach to overcome challenges associated with nanoparticle (NP) production, through the environmentally friendly synthesis of nano-silica (NS) derived from olivine rock, specifically designed for construction applications. The results revealed that amorphous NS ranging from 7.9 to 43.4 nm could be successfully produced from olivine rock. Furthermore, incorporating 2% of this NS into geopolymer concrete mixtures resulted in a notable improvement in compressive strength, with enhancements of 13.09 and 13.07% at 28 and 90 days, respectively. The findings highlight the potential of olivine rock-based NS production, which could significantly impact the construction sector by enabling the affordable integration of NPs. Consequently, this advancement has the potential to increase the use of NPs in construction, leading to enhanced durability and strength in various construction materials.

Keywords Geopolymer concrete · Green synthesis · Mechanical property · Nano-silica · Olivine rock

Abbreviations

GPC	Geopolymer concrete
NS	Nano-silica
NS-C	Commercial nano-silica
NS-LM	Locally manufactured nano-silica
NP	Nanoparticles
GGBFS	Ground-granulated blast furnace slag
C–S–H	Calcium–silicate–hydrate
N–A–S–H	Sodium–alumino–silicate–hydrate
C–A–S–H	Calcium–alumino–silicate–hydrate
SF	Silica-fume
NaOH and SH	Sodium hydroxide
Na_2SiO_3 and SS	Sodium silicate
FA	Fine aggregate
CA	Coarse aggregate
XRD	X-ray diffraction
SEM	Scanning electron microscope
M	Molarity
EW	Extra water
SP	Superplasticizer

✉ Hemn Unis Ahmed
hemn.ahmed@univsul.edu.iq

1 Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimani, Kurdistan Region, Iraq

2 Civil Engineering Department, Komar University of Science and Technology, Sulaimani, Kurdistan Region, Iraq

3 Civil Engineering Department, University of Halabja, Halabja, Kurdistan Region, Iraq

4 Department of Chemistry, College of Science, University of Sulaimani, Sulaimani, Kurdistan Region, Iraq

5 Department of Geology, College of Science, University of Sulaimani, Sulaimani, Kurdistan Region, Iraq

Introduction

Nanomaterials refer to substances that possess at least one dimension measuring 100 nm or smaller, either on their outer surface or within their internal structure. These materials can adopt various physical forms such as particles, tubes, rods, or fibers [1, 2]. Nanomaterials with the same composition as known materials in bulk form may have different physicochemical properties and behave differently if introduced into the body. As a result, they may pose several potential dangers [3]. Nanomaterials are characterized by their incredibly small size, which grants them unique properties and behavior compared to their bulk counterparts. At

the nanoscale, the surface area-to-volume ratio increases significantly, leading to enhanced reactivity and interaction with their surroundings. This allows nanomaterials to exhibit novel physical, chemical, and biological properties that make them valuable for a wide range of applications in various fields [4, 5]. Furthermore, nanomaterials can occur naturally, be created as the by-products of combustion reactions, or be produced purposefully through engineering to perform a specialized function. These materials can have different physical and chemical properties to their bulk-form counterparts [6].

The scientific research community has embraced green and environmentally friendly synthesis methods for producing NPs. This could be due to its eco-friendliness and the use of non-toxic components throughout the synthesis process. Because of the exceptional growth and development in this sector, researchers have recently focused on nanotechnology, assuming it will improve society's standard of living [7]. Furthermore, NPs have attracted the attention of researchers worldwide due to their distinctive properties, such as shape, size, and distribution, which can be used in various applications [8].

Due to their ease of use, stability, low toxicity, exceptional biocompatibility, capacity to be functionalized with a range of polymers and compounds, tunable particle sizes, and low cost, silica nanoparticles have received a lot of interest recently in several applications [9]. Silica nanoparticles are being developed in various fields, including technology, the building industry, agriculture, the food industry, medicine, and consumer goods. These developments significantly impact changing and improving industries [10]. Additionally, silica nanoparticles have been widely utilized in the construction of modern buildings, particularly in concrete and cement-based materials, to boost compressive strength, the primary objective of civil engineers, and hence decrease cement consumption and greenhouse gas emissions [11].

Initial research [12] has shown that nano-silica can be generated by dissolving olivine in acids according to Eq. (1). Olivine, $(Mg, Fe)_2SiO_4$, is the quickest weathering silicate, and the Si–O–Si connections are broken more easily than in any other silicate mineral.

$$(Mg,\ Fe)_2SiO_4 + 4H^+ \rightarrow Si(OH)_4 + 2(Mg,\ Fe)^{2+} \quad (1)$$

The neutralization results in a mixture of inert minerals, precipitated silica, unreacted olivine, and a magnesium/iron salt solution. Sedimentation removes the unreacted substances and inert minerals from the final suspension once the reaction is finished. After that, washing and filtering can extract the silica from the final mixture [13].

Researchers are interested in creating nanocomposite building materials because NPs have unique physical and chemical properties due to their ultrafine particle sizes [14]. Geopolymers are a type of inorganic material produced by activating alkaline substances with a source of binder material rich in aluminum and silicates [15, 16]. These binder materials can include fly ash, metakaolin [17], and ground-granulated blast furnace slag [18]. Geopolymers are an environmentally construction materials due to employing a wide range of waste materials in their mixture ingredients [19]. NPs were introduced with geopolymer matrices to enhance durability issues, physical structure, and mechanical properties of the geopolymer mixture [20]. NPs have a greater surface area to volume ratio, making them highly reactive and influencing reaction rates [21]. Therefore, NPs alter the microstructure of geopolymer concrete at the atomic level, resulting in significant improvements in both fresh and hardened state characteristics and structural behavior, without the use of heat [22]. Moreover, studies have indicated that incorporating varying amounts of nano-eggshell powder [23], nano-cotton stalk ash [24], nano-silica [25–27], nano-sesame stalk ashes [28], and modified nano-titanium [29] into concrete mixtures improves several characteristics of high-strength concretes.

Currently, the two main techniques used in the commercial production of nano-silica are flame hydrolysis and the neutralization of sodium silicate solutions with acid, resulting in precipitated or pyrogenic silica. However, these methods are expensive due to the high cost of raw materials and the substantial energy requirements involved [13]. If a new, cost-effective industrial production method could be developed, the potential applications of NS could be significantly expanded. Hence, this study aims to propose a green synthesis approach for the production of NS by utilizing a hydrothermal process applied to naturally occurring olivine rock found in the Mawat Town of Sulaimaniyah city in the Kurdistan region of Iraq. The proposed green synthesis method has the potential to revolutionize the production of nano-silica by providing a more sustainable and affordable alternative. The utilization of locally available olivine rock as a precursor for silica extraction ensures a steady supply of raw materials while reducing dependency on expensive imports. Additionally, the use of a hydrothermal process offers the advantage of energy efficiency, making the production process more economical and environmentally sound. Ultimately, this research strives to contribute to the advancement of green technologies and promote sustainable practices in the field of nano-material production.

Research significance

The importance of the study lies in its investigation of a green synthesis technique for converting the naturally occurring mineral olivine rock into nano-silica. The ecologically friendly alternative to traditional techniques of generating

nano-silica is provided by this sustainable methodology. The influence of adding this locally obtained nano-silica to geopolymer concrete composites is also investigated in the study. The goal of the research is to advance the creation of stronger, more durable construction materials by analyzing the mechanical performance of these composites. This research holds great value in advancing the field of eco-friendly construction materials and promoting the utilization of natural resources in an efficient and sustainable manner.

Experimental program and methodology

Manufacturing process of nano-silica

The olivine rock was taken from a mountain near Mawat Town-Sulaimaniyah city-Kurdistan region-Iraq. To begin producing amorphous nano-silica (SiO_2) from olivine rock (Mg, Fe) $2SiO_4$, olivine rock was crushed to produce microscopic granular particles that ranged in size from 1 to 5 mm. After that, the crushed olivine granular particles were washed with warm water to remove dust and other impurities and contaminations. Then, based on the study conducted by Lazaro [13], three moles of sulfuric acid (H_2SO_4) solution were used as the reagent decompositions. Therefore, 30 g of olivine granular particles were mixed with 250 ml of 3 M sulfuric acid. After that, the mixture was heated at 90 °C for about 4 h. A stirrer was used to stir the solution, while it was being heated so that the acid reagent would react and come into contact with all of the rock's bits, causing more deterioration and extracting more silica from the olivine granules. The combination was then cooled to the lab's ambient temperature.

The produced silica was then separated from the residual olivine granules using distilled water. After that, the decantation technique was used to separate the nano-silica from the residue since it was suspended inside the distilled water solution, which has a white color. To separate the nano-silica particles from the distilled water, a centrifuge at 5000 rpm for about 10 min was employed. The washing was carried out three times until the pH of the water was between 5.5 and 7. After that, silica mud was dried at 110 °C in an oven until all the solvents evaporated. Finally, the nano-silica was produced [13, 30].

Figure 1 depicts every step of the nano-silica production process. The kinetics of olivine dissolution and the nano-silica washing steps are the key process variables that affect the texture and specific surface area of nano-silica. By altering the production parameters, it is possible to customize the properties of this micro-silica [13]. Lastly, because of the low cost of the raw ingredients and the low energy required of this process (the temperature is around 90 °C and the reaction is exothermic), the cost of this nano-silica should be lower than the cost of commercial nano-silica. As a result, olivine nano-silica could be used in new domains where it is currently prohibited due to its high cost.

Materials used for the preparation of GPC

The primary binder material for producing geopolymer concrete mixtures was ground-granulated blast furnace slag (GGBFS). GGBFS is composed of approximately 11.64% aluminum oxide, 38.16% silicon oxide, and 30.97% calcium oxide in terms of its chemical composition. It possesses a specific gravity of 2.9. Additionally, in the geopolymer concrete mixtures, a fixed proportion of around 10% of the total binder content was comprised of silica-fume. The silica-fume used in the mixtures had a silicon oxide content of approximately 92.4% and a specific gravity of 2.25. Furthermore, hydrophilic NS particles in a powdered form were supplied by a Chinese company called LUOYANG. These particles, with sizes ranging from 30 nm and a specific gravity of 0.7, were employed.

For enhancing the workability of the concrete mixtures, a superplasticizer named Hyperplast PC900, manufactured by DCP company, was utilized. This superplasticizer is known for its ability to maintain slump and complies with ASTM C494, TYPE G standards. It has a specific gravity of 1.12 g/cm^3 and a pH value between 5 and 7. The aggregates used in the mixtures consisted of well-graded crushed coarse aggregates and natural river fine aggregates, meeting the requirements of ASTM C33. The specific gravities of the coarse and fine aggregates were 2.69 and 2.7, respectively. The coarse aggregate had a maximum size of 12.5 mm and a water absorption rate of 1.37%, while the fine aggregate had a water absorption rate of 1.73%.

To form the alkaline liquid for the geopolymer concrete mixtures, a combination of 12 M sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions was used. These solutions were obtained from the Malbray chemical factory in Erbil, Kurdistan Region, Iraq. The NaOH was in pellet form with a purity of 98%, while sodium silicate was in liquid form and consisted of 37.5% SiO_2, 16.5% Na_2O, and 46% H_2O. The specific gravity of sodium silicate was 1.34, and for sodium hydroxide, it was 1.5.

Mix proportions

In the laboratories of the civil engineering department at the University of Sulaimani's College of Engineering, several geopolymer concrete mixtures were prepared. These mixtures incorporated different amounts of NS ranging from 0 to 4%. The mix design procedures followed the methodologies described by Reddy et al. [31]. The goal was to achieve a well-balanced composition that considered factors such as cost-effectiveness, workability, strength, durability, density,

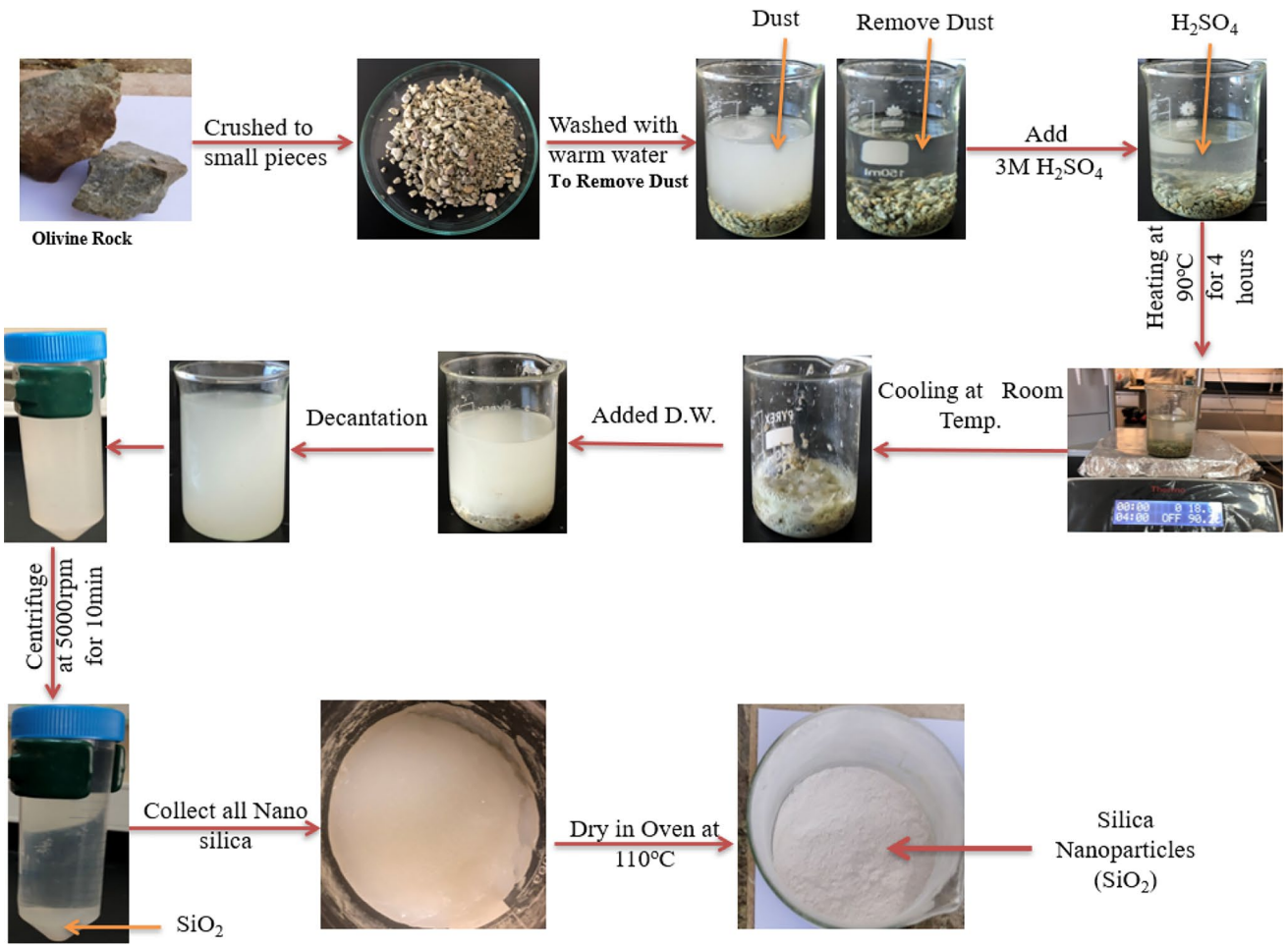

Fig. 1 Schematic synthesis of silica nanoparticles (SiO_2) from olivine rock by hydrothermal method

and appearance. The initial stage involved five mixes, including a control mixture. Each mix replaced a specific percentage of the total binder content with NS particles: 1, 2, 3, and 4% of the total weight of the binder materials used. The mix names followed a systematic pattern, where G1 represented the control mixture with 0% NS particles, and G2 denoted a mixture with 1% NS content. The remaining mixes were named accordingly. All the mix proportions for the different mixtures are detailed in Table 1.

Mixing and casting

To ensure consistent and uniform mixtures in the production of the GPC mixtures, careful attention was given to the mixing sequence and duration. In this study, a constant mixing process and batching procedure were followed to achieve homogeneity across all mixtures. The mixing procedure consisted of three stages. In the first stage, fine and coarse aggregates were placed in a

Table 1 GPC mix proportions in kg/m^3

Mix ID	GGBFS	SF	NS	SH	SS	EW	SP	FA	CA
G1	400	50	0	64.3	160.7	24.75	9.45	612.28	1104.27
G2	395.5	50	4.5	64.3	160.7	24.75	9.45	607.55	1095.72
G3	391	50	9	64.3	160.7	24.75	9.45	602.82	1087.2
G4	386.5	50	13.5	64.3	160.7	24.75	9.45	598.10	1078.67
G5	382	50	18	64.3	160.7	24.75	9.45	593.37	1070.14

GGBFS ground-granulated blast furnace slag; *SF* silica-fume; *NS* nano-silica; *SH* sodium hydroxide; *SS* sodium silicate; *EW* extra water; *SP* superplasticizer; *FA* fine aggregate; *CA* coarse aggregate

power-driven revolving pan mixer and mixed for 30 s to achieve even distribution. In the second stage, previously dry-mixed powdered materials (including GGBFS, silica fume, and NS particles) were added to the mixer and blended with the aggregates for approximately 60 s. The third stage involved the gradual addition of the alkaline solution (prepared 24 h prior to mixing) and a mixture of extra water and superplasticizer, which were pre-mixed separately. The mixer ran for 180 s during this stage. Once the mixing process was completed, multiple samples were cast in molds with lubricated surfaces to assess various properties of the GPC mixes (as shown in Fig. 2). A vibrating table was employed to compact the fresh concrete and remove air bubbles. After 24 h, the specimens were demolded and left to cure in the laboratory at a controlled temperature of 23 ± 2 °C until they were ready for testing.

The mix names can be explained as follows: for instance, G1 represents the control mixture without any NS particles. G2-LM denotes a mixture with 1% of locally manufactured NS derived from olivine rock, and G3-LM indicates a mixture with 2% of locally manufactured NS also derived from olivine rock. The same naming convention is applied to the other mixtures in the study.

Results and discussion

X-ray diffraction (XRD)

X-ray diffraction (XRD) is a popular technique for characterizing NPs. The device has a Cu anode, a wavelength of 0.154 nm, a maximum power of 2.2 kW, a voltage of 60 kV, and a long fine-focus ceramic tube. The XRD powder diffraction pattern of NS made by a green technique utilizing olivine rock is shown in Fig. 3. A broad peak centered at $2\theta = 26°$ could be assigned to the SiO_2 NPs, and no other diffraction peaks can be found [9]. The X-ray diffractograms confirmed that the SiO_2 NPs were amorphous [32]. Furthermore, the broad peaks show an amorphous structure. The peaks were matched with the reference of the Joint Committee on Powder Diffraction Standards (JCPDS) file No. 89-0510 for SiO_2. It revealed no impurities peak for the artificially manufactured SiO_2 [33].

Furthermore, using Debye–Scherrer formula [34], as shown in Eq. (2), the diameter (D) of the produced nano-silica was calculated.

$$D = \frac{0.9\lambda}{\beta \cos\theta} \tag{2}$$

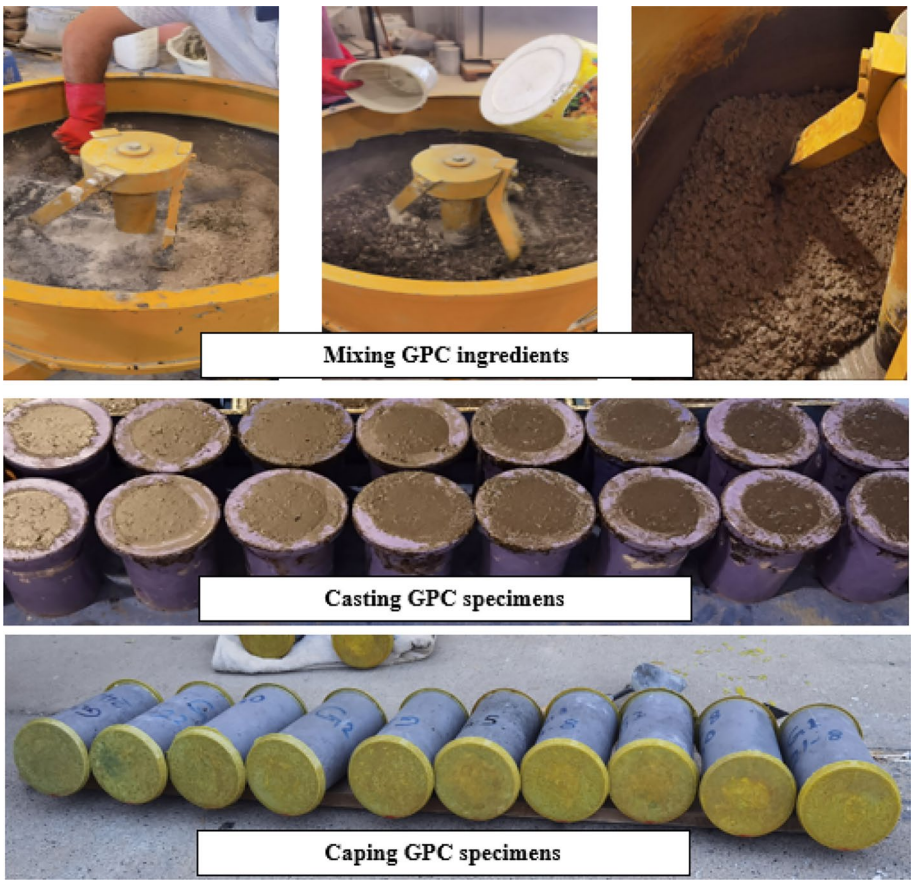

Fig. 2 Lab works for preparation of the GPC specimens

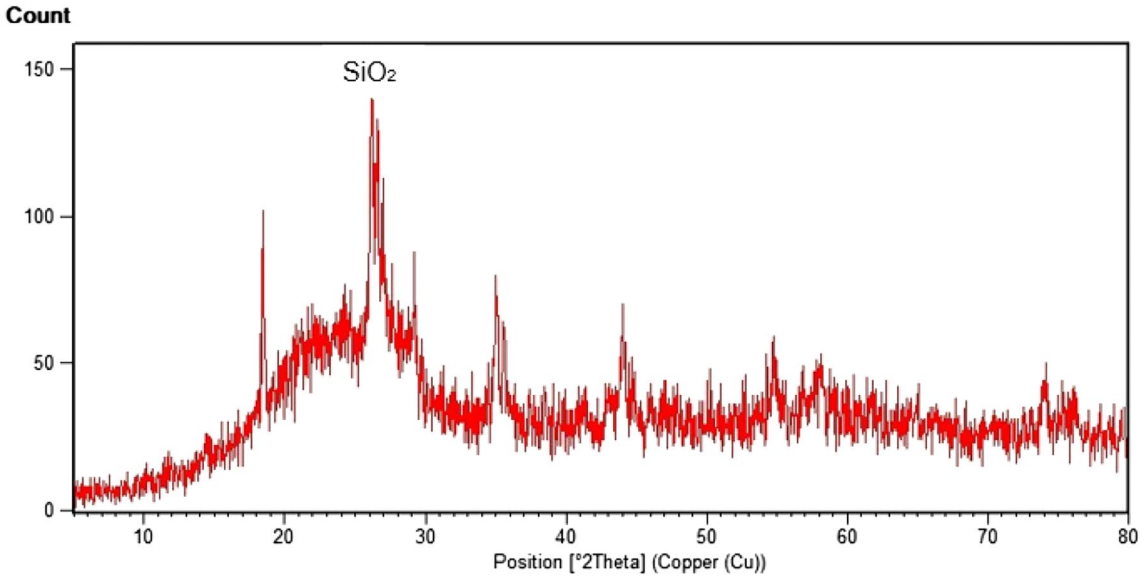

Fig. 3 XRD analysis for green synthesis nano-silica manufactured from olivine rock

Table 2 XRD peak indexing and diameter of green synthesized nano-silica manufactured from olivine rock

λ	2θ	FWHM	D^* (nm)
0.154	18.4422	0.192	41.9
0.154	26.1786	0.192	42.5
0.154	29.2445	0.288	28.5
0.154	35.0641	0.192	43.4
0.154	35.5876	0.288	29.0
0.154	44.0299	0.384	22.3
0.154	54.7562	0.576	15.5
0.154	57.9607	1.152	7.9
0.154	74.003	0.576	17.3

*D = (0.154 × 0.9)/(radians(FWHM)*Cos(radians(2θ/2)))

where λ is the wavelength of the utilized X-ray (λ = 0.154 nm), β is the full width at half maximum (FWHM) of the most intense peak, and θ is the Braggs angle [35]. The previous equation found that the sizes of the manufactured nano-silica particles were between 7.9 and 43.4 nm, as shown in Table 2. This is a very encouraging result, which was expected since naturally occurring olivine rock was utilized instead of the toxic chemicals for producing nano-silica particles.

Scanning electron microscope (SEM)

The scanning electron microscope (SEM) was utilized extensively to explore the impact of NPs on the microstructural improvement of different concrete composites over time by capturing high-resolution pictures [36]. Scanning electron microscopy played a crucial role in analyzing the surface structure of the silica nanoparticles (SiO_2 NPs), and the findings can be observed in Fig. 4. The SEM images clearly demonstrate that the majority of the SiO_2 NPs possess a spherical shape and fall within the nanoscale size range. Nonetheless, it is important to note that significant agglomeration is observed among the SiO_2 nanoparticles, which is a common occurrence in the green synthesis technique. This phenomenon can be attributed to the inherent nature of nanoparticles, as their larger surface area leads to increased interaction and bonding, resulting in the formation of aggregates during the dehydration process [37]. Consequently, during the process of dehydration, these nanoparticles tend to unite and form aggregates, resulting in the observed agglomeration. This occurrence emphasizes the need for careful consideration and effective control strategies when synthesizing silica nanoparticles using the green synthesis method, as it directly impacts their dispersion and overall surface characteristics.

The SiO_2 NPs stick together, creating asymmetrical clusters independently [33]. The fabrication of SiO_2 NPs is affected by several growth variables, including growth time, SiO_2 concentration inside the olivine rock, pH value of the solution, and temperature. As a result, calibrating these growth components is crucial for achieving the required shape and size of nanoparticles, allowing maximum modification and request.

Mechanical property of GPC

Compressive strength is one of the essential mechanical characteristics of concrete structures, and it usually provides

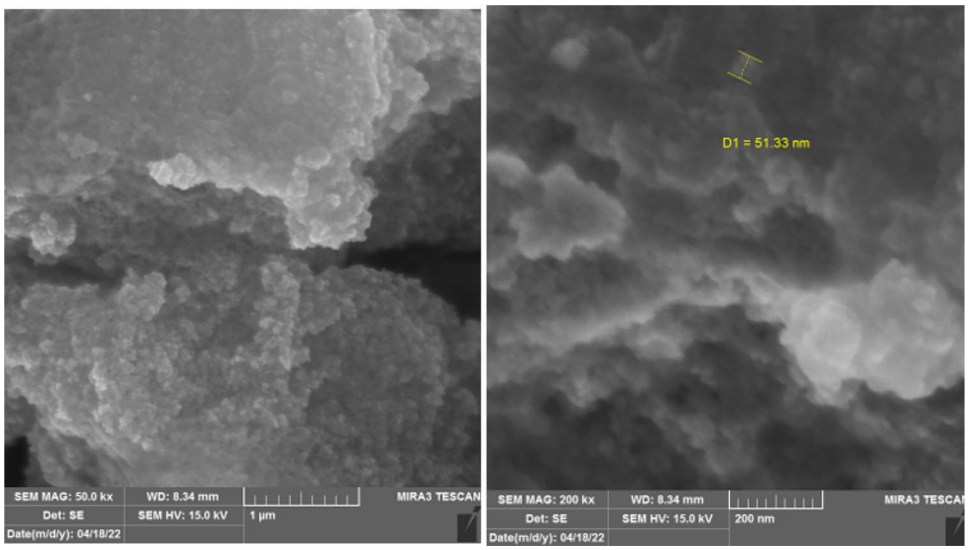

Fig. 4 SEM image of green nano-silica manufactured from olivine rock

a general performance regarding the quality of the concrete [38]; the same is true for geopolymer concrete. As a result, manufactured nano-silica derived from natural olivine rock was employed in GPC mixtures to demonstrate the effectiveness and influence of manufactured nano-silica on the compressive strength of GPC, as well as to compare commercially available NS and locally created NS. Four different GPC mixtures were prepared with 1, 2, 3, and 4% of manufactured NS, and then, the GPC samples were tested at the age of 28 and 90 days.

Figure 5 illustrates the differences in compressive strength values of commercial nano-silica (NS-C)-based geopolymer concrete, locally manufactured nano-silica (NS-LM)-based geopolymer concrete, and control geopolymer concrete specimens without any NS doses. Overall, it was discovered that adding NS-LM to GPC mixes improved compressive strength in all NS-LM dosages. Unlike the NS-C, the optimum dosage of NS-LM was 2%, which yielded GPC specimens with the highest compressive strength; nevertheless, the best dosage of NS-C was 3%. The compressive strength of GPC specimens after twenty-eight days increases as different NS-LM dosages are added. The maximum improvement in the compressive strength of about 13.09% was observed for GPC mixtures containing 2% of NS-LM, compared to the control GPC mixture. However, Fig. 6 demonstrates that the 3% NS-C content exhibits the greatest gain in compressive strength, reaching a value of 20.47% compared to the control GPC specimen without any NS doses. Furthermore, the close values of the increase in the compressive strength value of about 12.42% are noted in GPC samples incorporated 3% of NS-LM. Moreover, the enhancement in the compressive strength for the other NS-LM inclusions was 6.71% and 7.72% at 1% and 4% doses of NS-LM, respectively,

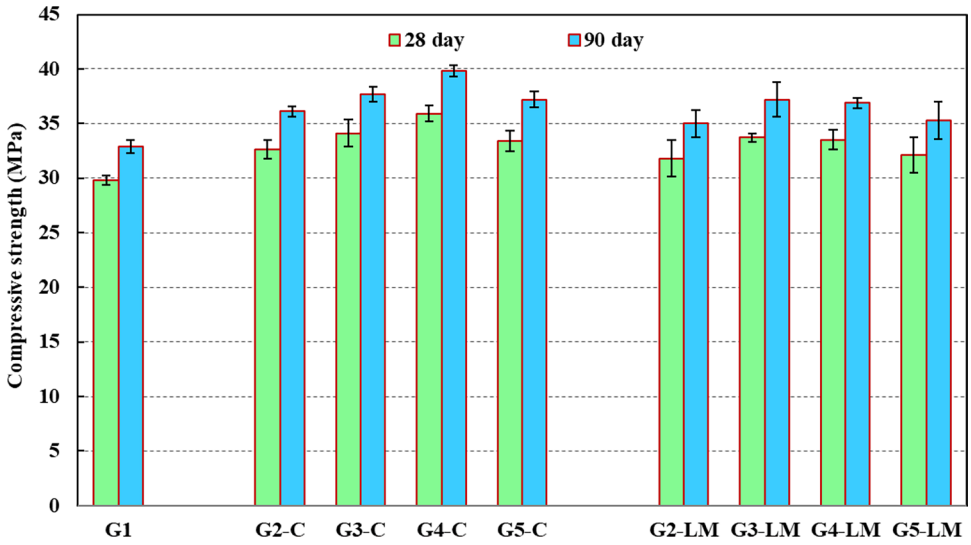

Fig. 5 Compressive strength of GPC mixtures with commercial and manufactured NS

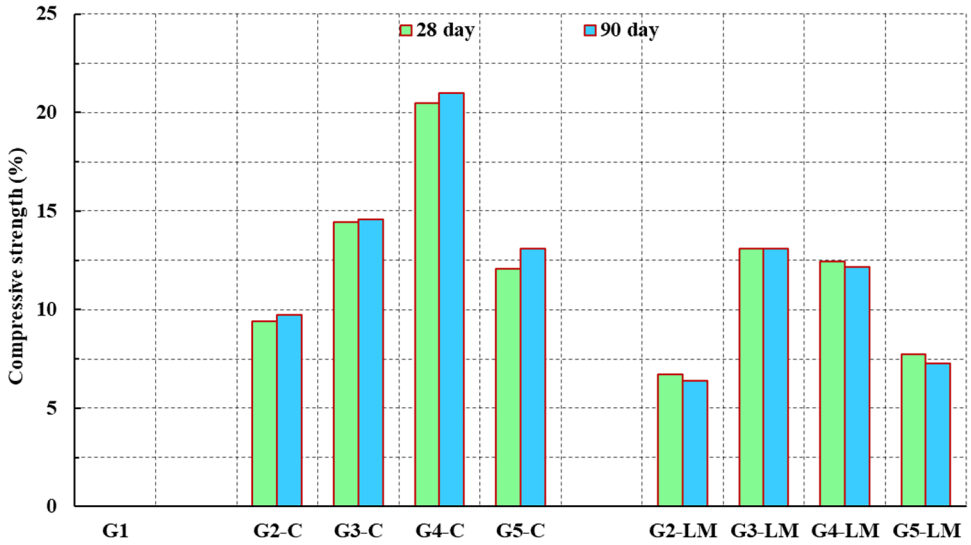

Fig. 6 Percent of compressive strength improvement in GPC mixture with commercial and manufactured NS compared to control GPC mixture

compared to the virgin GPC mixture. The remarkable enhancement in the compressive strength of GGBFS-based geopolymer concrete containing NS, especially with 3% NS-C and 2% NS-LM, could be attributed to the enhanced transformation of source materials to the polymeric gel such as C–S–H, N–A–S–H, and C–A–S–H gels in the presence of highly reactive NS, as well as a possible particle packing effect of nanoparticles in the binder structure by filling nano-pores within the geopolymer concrete matrixes, which, in turn, improves the specimens' strength [39, 40]. On the other hand, the compressive strength reduction was attributed to the matrix's overflowing availability of unreacted NS particles. The excess amount of NS caused agglomerations between the NS particles, which could have prevented silica dissolution, resulting in the formation of voids and, as a result, a decrease in the compressive strength of the geopolymer concrete; in addition, poor dispersion of NPs within the concrete mixtures counted as another reason for the decline in the compressive strength [36].

The compressive strength of GPC slightly increased as it aged from 28 to 90 days. However, the effect of adding NS-LM to the GPC mixtures at the ambient curing ages of 28 days was slightly higher than at 90 days. The average compressive strength of the control GPC specimens after 90 days was 32.9 MPa; however, for the NS-LM concentrations of 1, 2, 3, and 4%, respectively, this value increased to 35, 37.2, 36.9, and 35.3 MPa. For the same preceding GPC mixtures, these values were greater than the control GPC mixture by 6.38, 13.07, 12.16, and 7.29%, respectively. Similarly, the improvement in the compressive strength of different source binder material-based geopolymer concrete composites was also reported in the literature when different dosages of NS have introduced to the geopolymer concrete mixtures [41–43].

Referring to Figs. 5 and 6, it is concluded that the optimum dosages of NS for getting the highest compressive strength of GGBFS-based geopolymer concrete were 3%. Similar results have been reported in the literature by Behfarnia and Rostami [40]; however, Alzeebaree [44] and Mohammedameen [45] demonstrated that 2% of NS was the optimum dosage for getting maximum compressive strength of GGBFS and fly ash-based self-compacting geopolymer concrete composites, respectively. On the other hand, Ibrahim et al. [39] reported that a 5% replacement of natural pozzolan with NS gives maximum compressive strength to the natural pozzolan-based geopolymer concrete specimens.

Figure 7 illustrates the compression failure mode of both control and NS-GPC specimens, as seen in all GPC mixtures. Through visual observations during compressive strength tests, it was observed that the failure mode of GPC mixtures remained relatively consistent and maintained their shape under all conditions, particularly at the ultimate load. The predominant mode of failure was found to be ductile rather than brittle, indicating a tendency to exhibit flexibility. Additionally, the introduction of NS into GPC mixtures was observed to have a marginal impact, making the specimens slightly more prone to brittleness.

Referring to the findings above, it was discovered that the newly created NS affects the compressive strength of GPC mixtures comparable to those of commercially imported NS. Furthermore, the optimum dosage of this new type of NS is 2%, while the ideal dosage of NS-C was 3%. Finally, it will be interesting to generate NS in a more environmentally friendly manner in naturally occurring rocks in the Kurdistan region's mountains. As a result, this study is regarded as a first step toward mass-producing NS on a big scale by building necessary and crucial accessories and factories in this field. On the other hand, ongoing research and development in this subject are critical for gaining sound

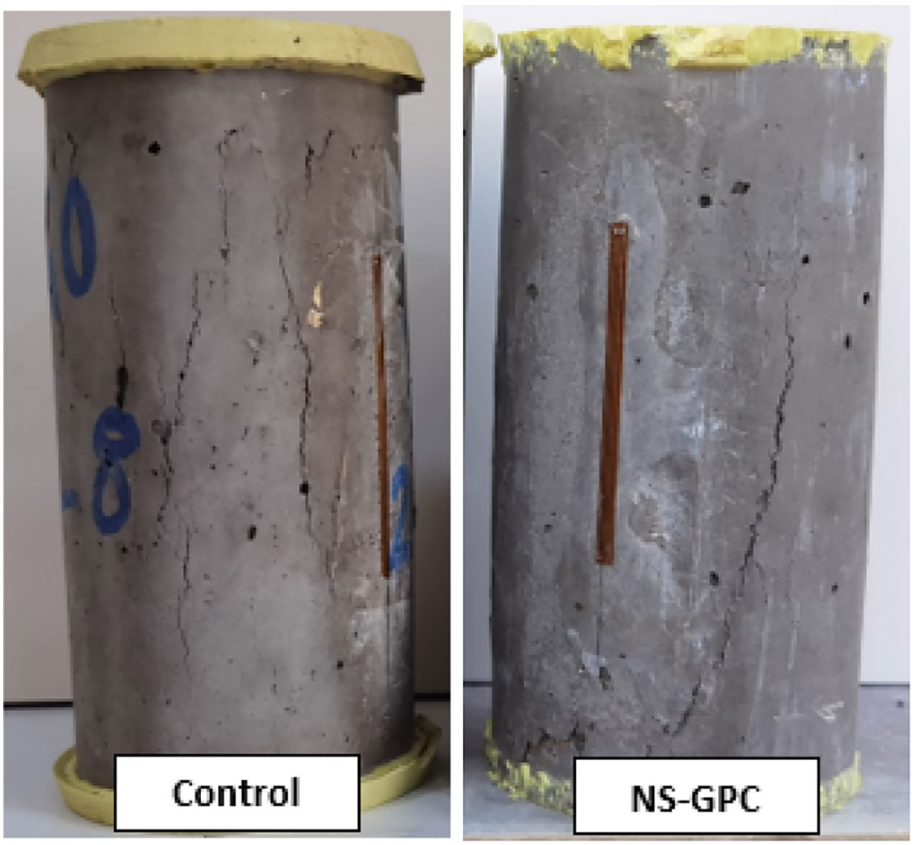

Fig. 7 GPC specimen failure patterns under compression test

engineering knowledge related to the uses and impacts of this new type of NS on the various engineering properties of all types of concrete composites, including geopolymer concrete composites.

Conclusions

Following an experimental program conducted in the laboratory to synthesize nano-silica from olivine rock and evaluate its effects on the mechanical property of geopolymer concrete, the following conclusions were drawn:

I. This project successfully commenced the initial phase of locally generating NS from olivine rock, marking a significant milestone in the research. Building upon this achievement, further steps will be taken to advance the process and explore its potential applications.
II. The XRD analysis revealed that the produced NS possesses an amorphous configuration, indicating the absence of a well-defined crystalline structure. The diameter measurements obtained from the analysis ranged from 7.9 to 41.9 nm, showcasing the diversity in size within the manufactured NS samples.
III. The compressive strength of the geopolymer concrete mixtures exhibited an upward trend with increasing dosages of NS-C, reaching its peak at 3% dosage before gradually declining. Additionally, as the samples aged, the compressive strength values experienced growth. The most significant enhancement in compressive strength was observed at a 3% NS-C dosage, resulting in a 20.5 and 21% improvement compared to the control geopolymer concrete mixture after 28 and 90 days of curing, respectively.
IV. The geopolymer concrete mixes demonstrated an increase in strength with the addition of NS-LM, reaching a peak at a 2% dosage, after which the strength gradually decreased. Furthermore, as the samples aged, their compressive strength values continued to rise. The most significant enhancement in strength was observed at a 2% NS-LM dosage, resulting in a remarkable improvement of 13.09 and 13.07% in compressive strength after 28 and 90 days of curing, respectively, when compared to the control geopolymer concrete mixtures.
V. The effectiveness of locally manufactured NS in enhancing the compressive strength of geopolymer concrete mixes was found to be similar to that of commercially accessible NS.

VI. For geopolymer concrete mixtures, the ideal dosage of commercially available NS was determined to be 3% of the total binder content to achieve optimal compressive strength values. In contrast, the optimum dosage of locally produced NS was found to be 2% for the same purpose.

Recommendations

After thorough the experimental program, the following recommendations have been raised:

(a) Examine the effect of olivine-based NS on the microstructure of geopolymer concretes.
(b) Effect of different curing conditions such as oven and steam for the GPC specimens with the inclusion of this NS on the mechanical behavior of the GPC.
(c) One of the major challenges in ensuring the level of nanomodification is NP dispersion in geopolymer composites; thus, additional research is needed to assess better and characterize NP dispersion in geopolymer composites.
(d) There is a dearth of research evaluating the life-cycle sustainability of geopolymer composites incorporated NS.
(e) Cost analysis between the manufactured NS and the exported NS.
(f) Examine the impact of adding this manufactured NS on the different properties of traditional cement-based concrete composites.

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Availability of data and materials All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study formal consent is not required.

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